

Searches for light new physics. Theoretical overview

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Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report

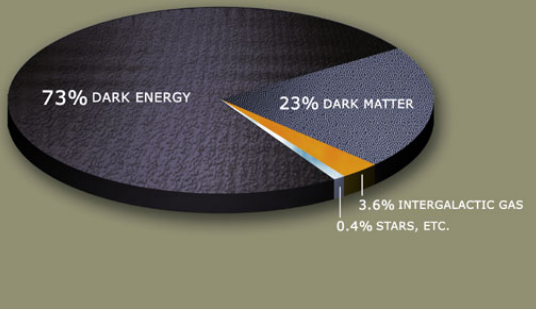
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•CERN-PBC-REPORT-2018-007

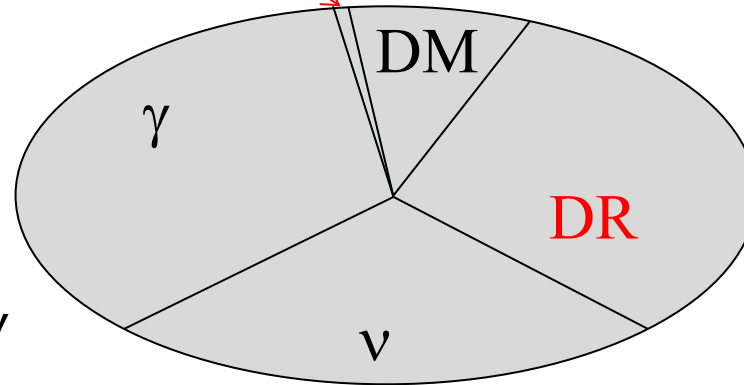
•e-Print: [arXiv:1901.09966](#) [hep-ex]

Particle “content” of the Universe is largely unknown



Atoms

In Energy chart they are 4%. In number density chart $\sim 5 \times 10^{-10}$ relative to γ



We have no idea about DM number densities. (WIMPs $\sim 10^{-8} \text{ cm}^{-3}$; axions $\sim 10^9 \text{ cm}^{-3}$. **Dark Radiation, Dark Forces – We don't know**).

Number density chart for axionic universe:

axions

Lack of precise knowledge about nature of dark matter leaves a lot of room for existence of dark radiation, and dark forces – dark sector in general.

New IR degrees of freedom = light (e.g. sub-eV) beyond-Standard-Model states

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out

$$\mathcal{L}_{\text{SM+BSM}} = -m_H^2 (H_{\text{SM}}^+ H_{\text{SM}}) + \text{all dim 4 terms } (A_{\text{SM}}, \psi_{\text{SM}}, H_{\text{SM}}) + \\ (\text{Wilson coeff. } / \Lambda^2) \times \text{Dim 6 etc } (A_{\text{SM}}, \psi_{\text{SM}}, H_{\text{SM}}) + \dots$$

But is this framework really all-inclusive – it is motivated by new heavy states often with sizeable couplings?

The alternative possibility for New Physics – weakly coupled light new physics - is equally viable

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all lowest dimension portals $(A_{SM}, \psi_{SM}, H, A_{DS}, \psi_{DS}, H_{DS}) \times$
portal couplings

+ dark sector interactions $(A_{DS}, \psi_{DS}, H_{DS})$

SM = Standard Model

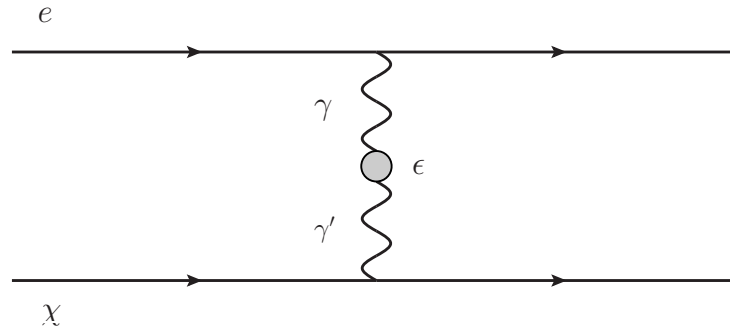
DS – Dark Sector

A simple model of dark sector

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi} [\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi] \psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi} [\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi] \chi,$$



- “Effective” charge of the “dark sector” particle χ is $Q = e \times \epsilon$ (if momentum scale $q > m_V$). At $q < m_V$ one can say that particle χ has a non-vanishing *EM charge radius*, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can “communicate” interaction between SM and dark matter. Very light χ can be possible.

Classes of portal interactions

Let us *classify* possible connections between Dark sector and SM

$H^+ H (\lambda S^2 + A S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ “Kinetic mixing” with additional U(1)’ group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that

Nature may have used the LHN portal...

Dim>4

$J_\mu^A \partial_\mu a / f$ axionic portal

.....

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

Excellent framework for light DM

some WIMP examples

- Scalar dark matter talking to the SM via a “dark photon”
(variants: L_{μ} - L_{τ} etc gauge bosons). With $2m_{\text{DM}} < m_{\text{mediator}}$.

$$\mathcal{L} = |D_{\mu}\chi|^2 - m_{\chi}^2|\chi|^2 - \frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2V_{\mu}^2 - \frac{\epsilon}{2}V_{\mu\nu}F_{\mu\nu}$$

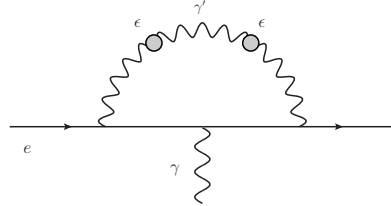
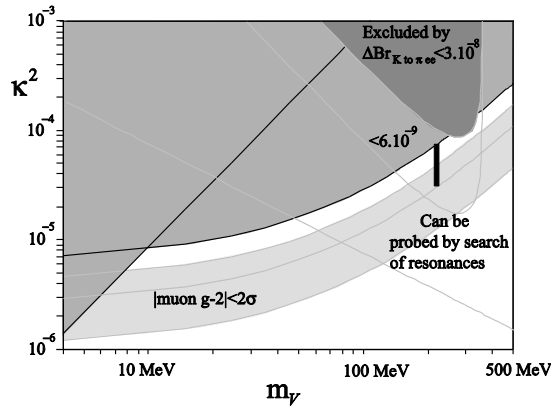
- Fermionic dark matter talking to the SM via a “dark scalar” that mixes with the Higgs. With $m_{\text{DM}} > m_{\text{mediator}}$.

$$\mathcal{L} = \bar{\chi}(i\partial_{\mu}\gamma_{\mu} - m_{\chi})\chi + \lambda\bar{\chi}\chi S + \frac{1}{2}(\partial_{\mu}S)^2 - \frac{1}{2}m_S^2S^2 - AS(H^{\dagger}H)$$

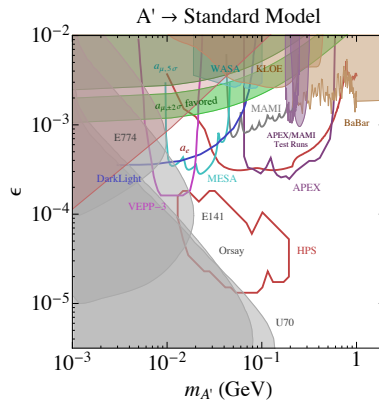
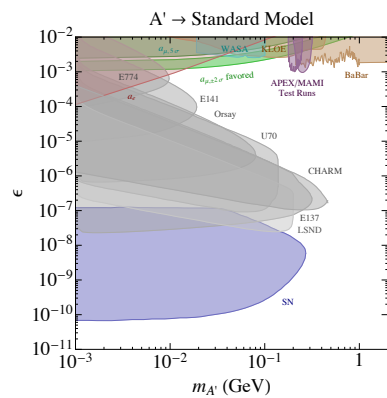
After EW symmetry breaking S (“dark Higgs”) mixes with physical h , and can be light and weakly coupled provided that coupling A is small.

Take away point: *with lots of investment in searching for DM with masses $> \text{GeV}$, models with sub-GeV DM can be a blind spot.*

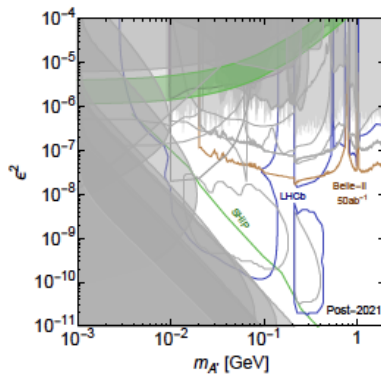
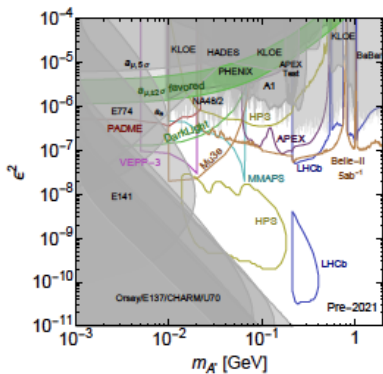
g-2 motivation for dark photons



Dark photon with kinetic mixing $\sim 10^{-3}$ is the simplest model that can account for anomalous $\Delta a_\mu \sim 3 \cdot 10^{-9}$, MP, 2008



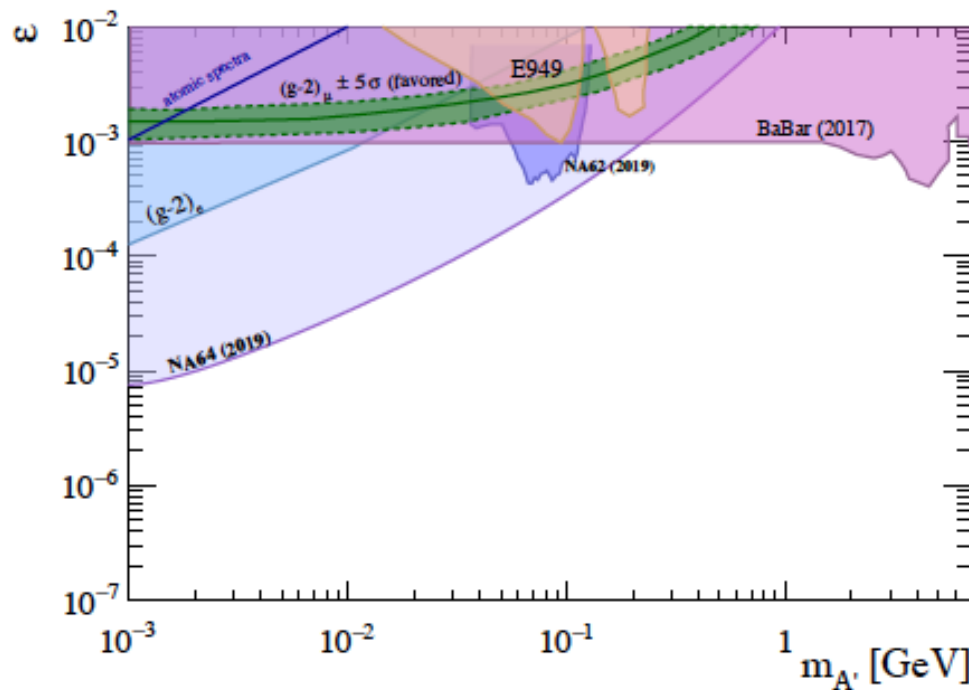
Search for dark photons ($A' \rightarrow e^+e^-$) has become an important part of the intensity frontier program, Snowmass exercise, Minneapolis, 2013



By 2018, there is a large community in place ("Cosmic Vision" summary, 100s of authors, 2017), where the search for dark photon is one of the priorities.

Pair production of dark matter via vector portal

If dark photon decays invisibly, for example to a pair of DM particles, the search for dark photon is the search for “anomalous energy loss”, such $e^+e^- \rightarrow \gamma + A' \rightarrow \gamma + \chi\chi$



Plot is from recent review [M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, 2005.01515](#). NA64, in particular, probes the part of parameter space motivated by the freeze-out dark matter.

Are there any more models that can correct $g-2$?

This year [hopefully] the Fermilab-based experiment is going to present results that more than double the existing dataset.

Independently of that one can question whether other models can provide viable upward correction to $g-2$.

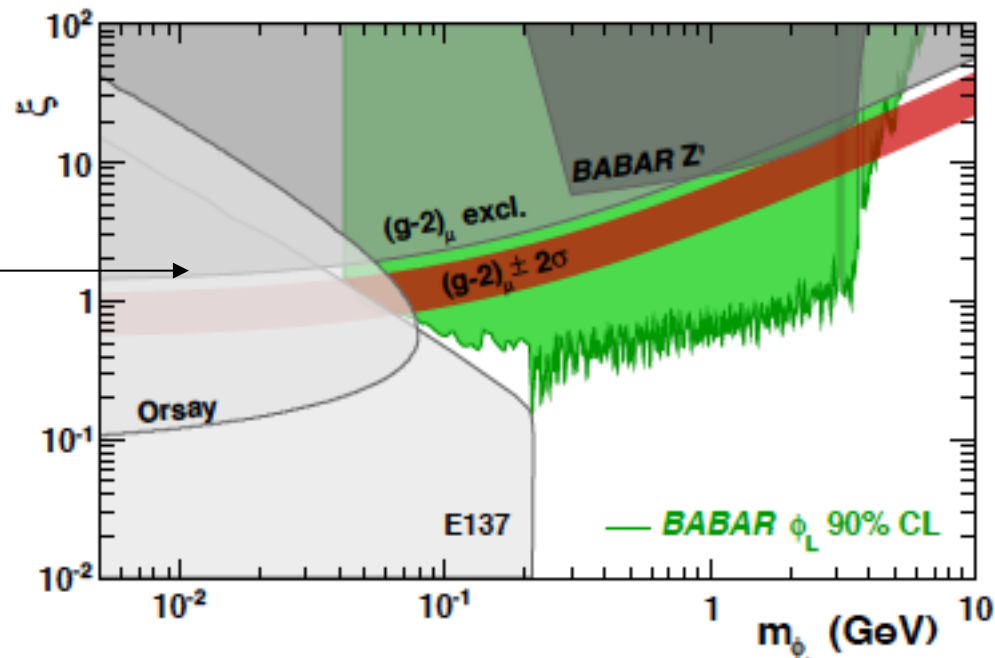
- Models based on muon-tau lepton number, with gauge coupling at $g \sim 10^{-3}$ level and mass above ~ 10 MeV (BBN) and below ~ 210 MeV (4-muon signal at B-factories, + trident neutrino + high-energy excludes higher masses). These models can be probed with NA64 style experiment with incoming muons (Gninenko, Krasnikov et al.)
- Models based on scalars coupled to leptons with “new Yukawa” at the level of SM Yukawa, but with light scalars. They are hard to build (see e.g. Batell et al., 2016, Chen et al, 2015)

Recent constraints from BaBar

In a minimal flavour violation framework, the coupling to leptons is proportional to their masses. Therefore the bremsstrahlung of scalars in $e^+ + e^- \rightarrow \tau^+ + \tau^- + \text{Scalar}$, with its subsequent decay to electrons or muons, is the promising channel (Batell et al, 2017)

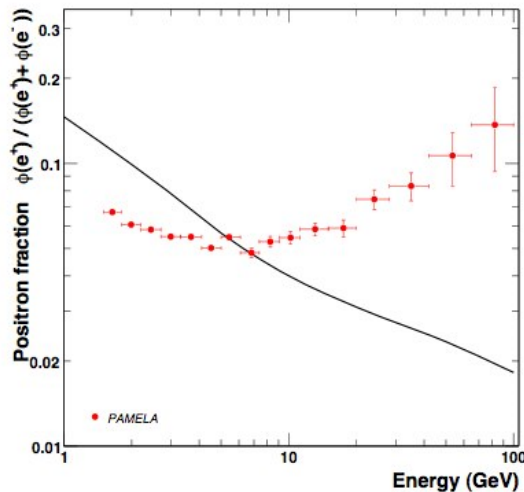
In an impressive new analysis led by B. Echenard and B. Shuve, Babar published a constraint from a corresponding search:

Beam dump regions are slightly too optimistic, based on old "recast", and will be updated soon.



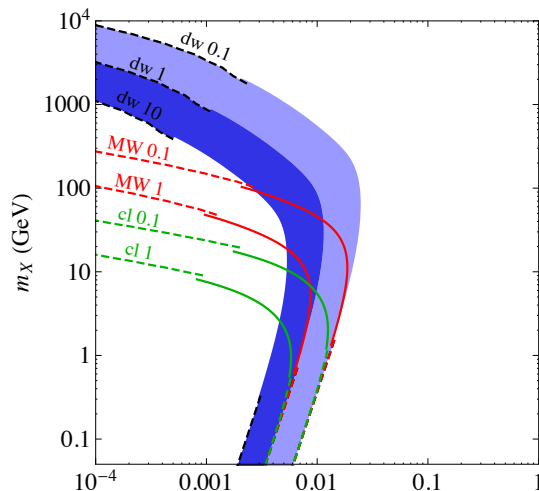
New Physics paradigm that include light particles have enormous flexibility in "explaining" anomalies

- For example, cosmic positron fraction ("Pamela anomaly")



Light new mediator particles V can A. dynamically enhance the annihilation cross section at low velocity, B. kinematically limit the annihilation products to electrons and positrons.

- Self-interaction of dark matter can be an attractive possibility to address over-concentration of cold dark matter in the central parts of galactic haloes. Self-scattering cross section of $10^{-24} \text{ cm}^2/\text{GeV}$ implies that either DM or mediator is light, or both. (Plot from **Tulin et al.**)



Physics Beyond Colliders and its mission

- *an exploratory study aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments'*

An attempt for a comprehensive overview has been made in 2016 and 2017, and in the on-going **Physics Beyond Colliders exercise at CERN**

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),¹ Alberto Belloni (Coordinator),² Aaron Chou (WG2 Convener),³ Priscilla Cushman (Coordinator),⁴ Bertrand Echenard (WG3 Convener),⁵ Rouven Essig (WG1 Convener),⁶ Juan Estrada (WG1 Convener),³ Jonathan L. Feng

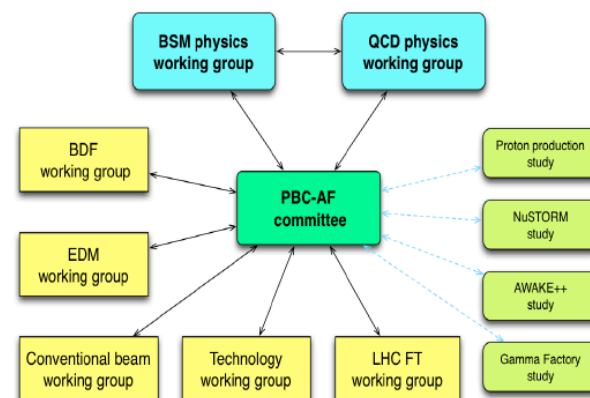
arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

... very long list of authors

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),¹ Marco Battaglieri (DMA Convener),² Bertrand Echenard (RDS Convener),³ Rouven Essig (Organizer),^{4,*} Matthew Graham (Organizer),^{5,†} Eder Izaguirre (DMA Convener),⁶ John Jaros (Organizer),^{5,‡} Gordan

CERN PBC exercise led by
Jaeckel, Lamont, Valtée



Models vs Experiments

Benchmark Cases (**MP and PBC, 2018**)

1. *Dark photon*
2. *Dark photon + light dark matter*
3. *Millicharged particles*
4. *Singlet scalar mixed with Higgs*
5. *Quartic-dominated singlet scalar*
6. *HNL, e -flavour dominance*
7. *HNL, μ -flavour dominance*
8. *HNL, τ -flavour dominance*
9. *ALPs, coupling to photons*
10. *ALPs, coupling to fermion*
11. *ALPs, coupling to gluons*

Experimental proposals, mostly CERN

- *SHiP*
- *NA62+*
- *FASER*
- *MATHUSLA*
- *Codex-B*
- *MilliQan*
- *NA64*
- *KLEVER*
- *REDTOP*
- *IAXO*
- *ALPs-II*
- *.....*

I hope that in the end, a clear strategy for building up CERN intensity frontier program will emerge, with new sensitivity to sub-EW scales 15

Models vs Experiments

Benchmark Cases (**MP** and **PBC**, 2018)

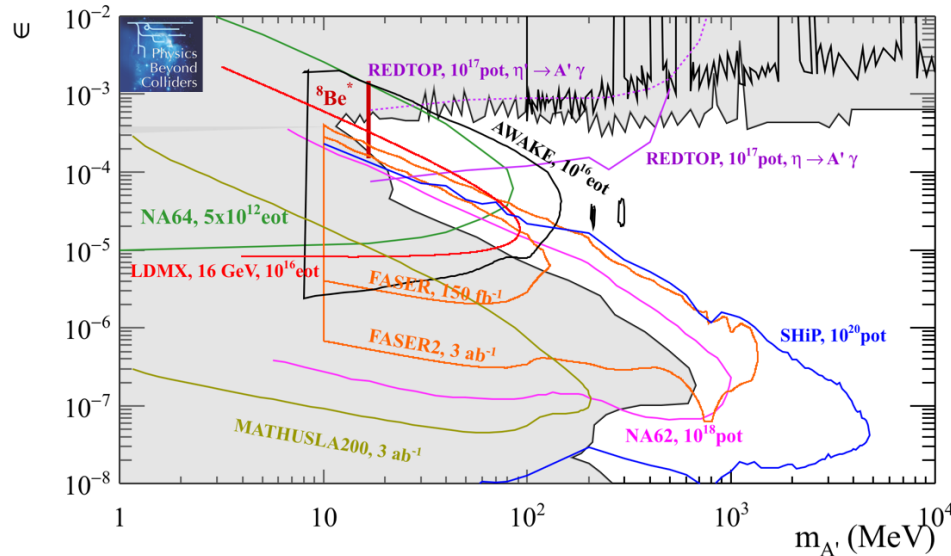
Experimental proposals, mostly CERN

1. <i>Dark photon</i>	Vector	▪ <i>SHiP</i>	<i>Beam Dump</i>
2. <i>Dark photon + light dark matter</i>		▪ <i>NA62+</i>	<i>Flavour, possible BD</i>
3. <i>Millicharged particles</i>		▪ <i>FASER</i>	<i>LHC add-on</i>
4. <i>Singlet scalar mixed with Higgs</i>		▪ <i>MATHUSLA</i>	<i>large LHC add-on</i>
5. <i>Quartic-dominated singlet scalar</i>		▪ <i>Codex-B</i>	<i>LHC add-on</i>
6. <i>HNL, e-flavour dominance</i>	HNL	▪ <i>MilliQan</i>	<i>LHC add-on</i>
7. <i>HNL, μ-flavour dominance</i>		▪ <i>NA64</i>	<i>missing momentum</i>
8. <i>HNL, τ-flavour dominance</i>		▪ <i>KLEVER</i>	<i>flavour</i>
9. <i>ALPs, coupling to photons</i>		▪ <i>REDTOP</i>	<i>fixed target</i>
10. <i>ALPs, coupling to fermion</i>		▪ <i>IAXO</i>	<i>axion exp</i>
11. <i>ALPs, coupling to gluons</i>	ALPs	▪ <i>ALPs-II</i>	<i>axion exp</i>
		▪ ▪ ▪	

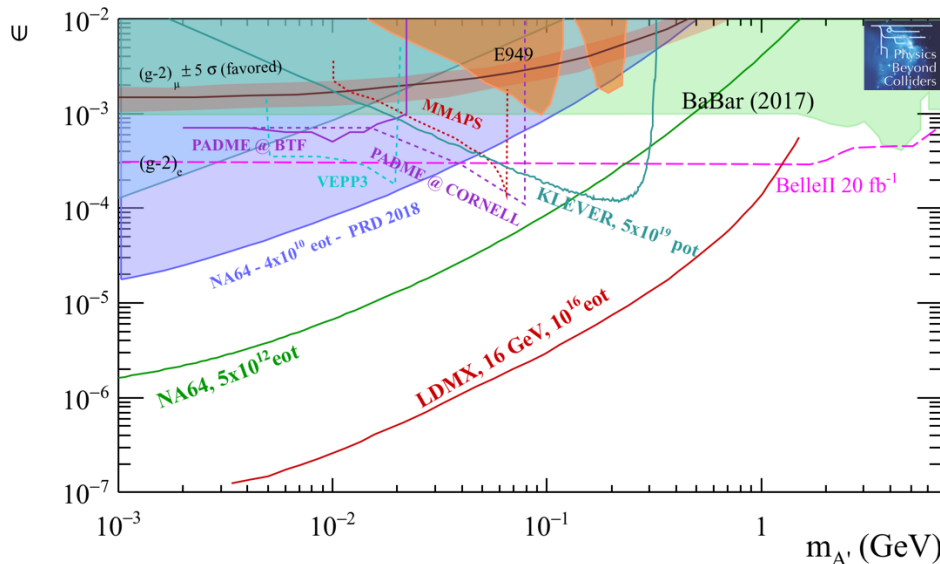
I hope that in the end, a clear strategy for building up CERN intensity frontier program will emerge, with new sensitivity to sub-EW scales 16

Highlights from recent PBC publication

G. Lanfranchi et al, BSM group

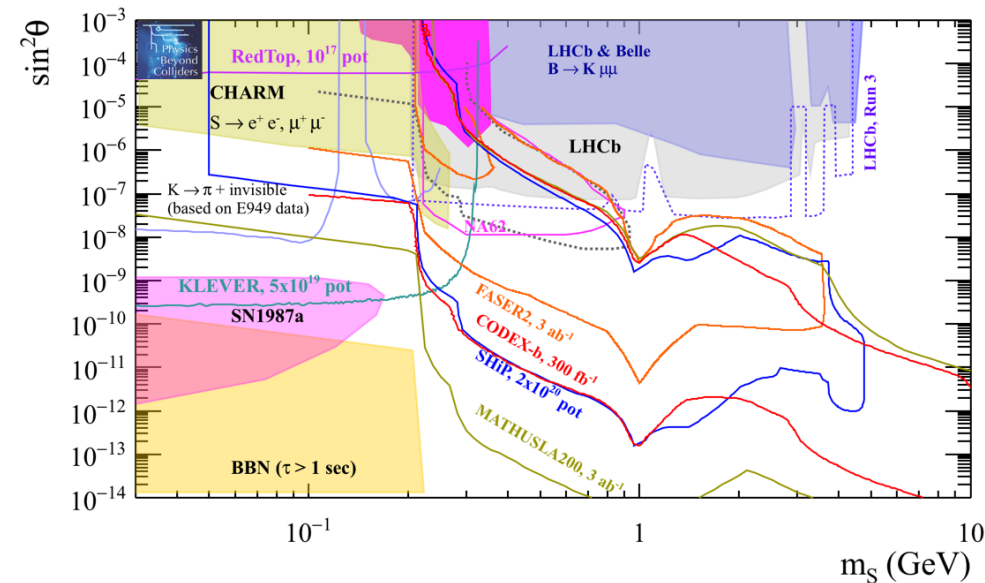


Benchmark cases 1 and 2,
models with visible [top]
and invisible [bottom]
decays of dark photons

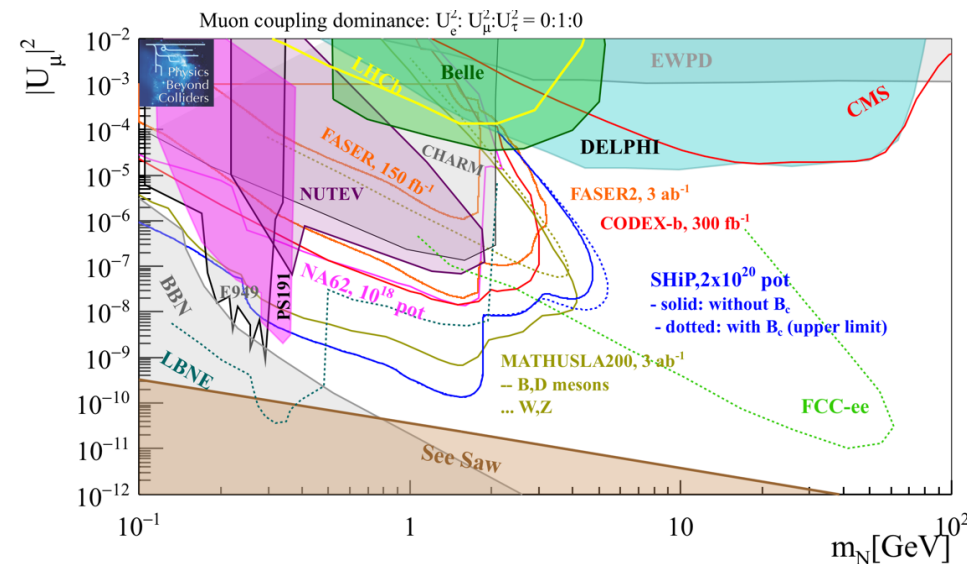


Highlights from recent PBC publication

G. Lanfranchi et al, BSM group



Benchmark cases 4 and 6,
models with Higgs-mixed
scalar [top] and muonic
HNL [bottom]



What did I learn from PBC BSM?

- PBC exercise has come up with an attempt of systematic approach to light New Physics in the sub-10-GeV regime. CERN will decide which experiments eventually to pursue [in addition to multi-decade LHC project].
- It paid off to have a uniform set of models $O(10)$ addressed by all collaborations.
- Scientific potential of our community is strong: in the process of PBC preparation several new ideas appeared, mistakes were corrected, and new results obtained (e.g. for the ALP coupling to gluons).
- Because of the PBC mandate, some of interesting physics was left out.
- What did PBC miss and/or under-emphasized and what Snowmass may choose to address?

Missing/under-explored 1

- Models with dim=6 and higher mediation, (SM current) \times (Dark current) = e.g. $(\bar{\psi}_{\text{SM}} \gamma_\mu \psi_{\text{SM}})(\bar{\chi}_{\text{DS}} \gamma_\mu \chi_{\text{DS}}) \times \Lambda^{-2}$, with subsequent decay and/or scattering of χ . (Many of these operators were explored in the DM at LHC studies, as well as LLP studies. Close to the hidden valley scenarios.)

This will emphasize collider connection more. Are there well-motivated yet economical frameworks that can be addressed by Snowmass?

Missing/under-explored 2

- Additional gauging of SM quantum numbers: $B-L$, $L_{\mu}-L_{\tau}$ and other possibilities.

If $m_V \ll \text{weak scale}$, $g \ll e$, making it perhaps more exotic than dark photon. Yet $L_{\mu}-L_{\tau}$ is less constrained if $m_V < 210 \text{ MeV}$, leaving some room for large $g-2$ of the muon correction. Perhaps worth including?

Note that *anomalous* symmetries, such as B , are well constrained by flavor.

Missing/under-explored 3

- Models with light-ish sterile neutrinos, capable of inducing interesting effects in neutrino physics. “Secret neutrino interactions”, including electromagnetic form-factors for active and sterile?

*PBC was *not* dealing with the neutrino physics other than with the “beam dump” mode. Yet many short baseline anomalies persist, and US community is in the best position to find out if some of it is new physics [or old misunderstood physics].*

Missing/under-explored 4

- Origin of mass in the dark sector, and "interplay" of portals. All vector portals dealing with massive A' took the Stuckelberg mass. Alternative [dark] Higgs origin of the mass has serious phenomenological consequences.

Is the Higgsed version of dark photon models worth including into studies?

Missing/under-explored 5

- Neutron portal to dark sectors. Interactions of type $(udd)\chi_{DS} \times \Lambda^{-2}$ can lead to several novel phenomena in neutron decays, rare decay type physics in underground detectors etc. If χ is Majorana – neutron-anti-neutron oscillations.

Would perhaps a minimal model of χ - n mixing at $O(10^{-10})$ level be worth including, as it provides an interesting bridge to nuclear physics?

Missing/under-explored 6

- LHC as an intensity machine, and in particular copious Z,W production. Certain rare modes, t were barely visible at LEP, such as $Z \rightarrow \mu\mu\gamma$, are now used to calibrate the detectors etc. They are under-utilized wrt new physics searches.

*PBC *mostly* stopped at 10 GeV invariant mass of new physics and probes. Should we make an effort to consistently expand all reported plots to the weak scale. (Done for subset of models.)*

Missing/under-explored 7

- More complicated energy level structures for Dark matter. Split – or inelastic dark matter – is giving a much wider range of phenomena both in direct detection and in colliders/beam dumps.

Perhaps should be included with simple 2-level structure and Δm between states into the analyses (done for some models).

Conclusions

From 2001 Snowmass where DM \sim QCD axions + neutralinos, 2013 made a big step into dark sectors. By 2020, both experimental and theoretical progress, put the systematic and inclusive studies of dark sectors firmly on the map of particle physics.

Are we missing any interesting/motivated physics in our theoretical models, and more importantly are there big experimental gaps that possibly need addressing?